PATENT SPECIFICATION

DRAWINGS ATTACHED

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COMPLETE SPECIFICATION

Improvements in or relating to Plasma Accelerators for Generating Propulsion Thrust

We, ROCKET RESEARCH CORPORATION, a corporation organized and existing under the laws of the State of Washington, United States of America, of 233 South Holden Street, Seattle, State of Washington 98108, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:

This invention relates to reaction propulsion engines and methods of operating same, and more particularly to rail type pulsed plasma accelerators having particular utility for satellite attitude control and station keeping and for primary propulsion of deep space probes and interplanetary space vehicles, for example.

According to the invention there is provided a pulsed plasma accelerator for generating propulsion thrust, comprising a pair of spaced, elongate substantially parallel electrodes of substatially equal cross-sectional area, a high voltage power supply connected across said electrodes, an electrical energy storage capacitor connected across said electrodes, an insulative container surrounding and being substantially coextensive with said electrodes at the sides and at one end thereof, leaving the other end open, and providing a plasma channelling chamber between said electrodes, a flux concentrator disposed laterally of the insulative container to provide an increased magnetic flux density therebetween, and and means for delivering and injecting a vaporizable and ionizable propellant into the closed end of said container.

According to one feature of the invention a ferromagnetic flux concentrator laterally surrounds said insulative container in a manner placing magnetizable pole pieces substantially against the side faces of said container so that plasma current self-induces an increased flux density within the plasma zone between said electrodes, with the flux lines thereof paralleling the thickness dimension of said container.

According to another feature of the invention there is provided a pulsed plasma accelerator wherein a vaporizable and ionizable propellant is injected into a plasma accelerating chamber open only at one end, said chamber in cross-section thereof lateral to the direction of plasma movement being generally rectangular in configuration bounded by electroconductive surfaces and insulative surfaces in alternating pattern, the total surface area of said insulative surfaces being substantially greater than the total surface area of said electroconductive surfaces, there being a flux concentrator disposed laterally of said insulative surfaces to provide an increased flux density therebetween.

Specific embodiments of the invention will now be described by way of example only with reference to the accompanying drawings in which:

FIG. 1 is a diagrammatic presentation showing the operation of a parallel rail pulsed plasma accelerator;

FIG. 2 is a plan view, with various parts broken away, of a typical confined parallel rail pulsed plasma accelerator, taken substantially along line 2-2 of FIG. 4;

FIG. 3 is a view in side elevation of the confined parallel rail accelerator shown in FIG. 2;

FIG. 4 is an end view of the confined parallel rail accelerator shown in FIGS. 2 and 3;

FIG. 5 is a cross-sectional view of a typical propellant flow modulator;

FIG. 6 is a fragmentary view in longitudinal cross-section and on an enlarged scale of a form of confined parallel rail pulsed plasma accelerator constructed according to the present invention, and incorporating a flux concentrator in the form of a ferromagnetic sheath, said view being taken substantially along line 6-6 of FIG. 7;

FIG. 7 is a view in lateral cross-section of the accelerator shown in FIG. 6, taken substantially along line 7-7 thereof;

FIG. 7A is a view in lateral cross-section showing a fragment of a modified form of confined rail accelerator according to the invention, wherein the electrode covering includes a flux concentrator in the form of a sheath of packed iron powder sheathed in epoxy resin;

FIG. 7B is a fragmentary isometric view of yet another form of confined rail accelerator and associated flux concentrating sheath, the ferromagnetic sheath in this modification being composed of a laminate of thin iron sheets and interleaved insulative sheets, with various portions of certain of the laminant sheets broken away to more clearly show the construction involved;

The operation of a pulsed plasma accelerator is diagrammatically illustrated in FIG. 1. Such accelerator in general functions to produce thrust from stored electrical energy. The basic accelerator configuration involves two spaced, elongate substantially parallel electrodes or rails 20, 22 which are connected across an electrical energy storage capacitor 24 and a high voltage power supply 26. When the capacitor 24 is charged, one of the rails is at a high voltage with respect to the other. No electrical breakdown occurs because these rails are located in a vacuum. However, when a small amount of propellant is injected or otherwise placed between the rails, a plasma column or "blob" 28 of ionized propellant forms between the electrodes 20, 22 and the electrical energy stored in the capacitor 24 discharges across the electrodes through the plasma column 28. The direction of current I in the electrodes 20, 22 during the discharge between the electrodes 20, 22 (as designated by arrows 20′, 22′) creates a reinforced magnetic field 30 in the region between said electrodes 20, 22 (as designated in FIG. 1 by crosses). The direction of the magnetic field 30 is perpendicular to the direction of the current I flowing in the plasma column 28 (which latter current is designated by arrow 28′). The interaction between the perpendicular magnetic field 30 and plasma current I (arrow 28′) creates a mutually perpendicular force accelerating the plasma column 28 down the electrodes 20, 22 and out of the accelerator, such accelerating force being shown by the arrow designated F. As will be understood, the accelerating force F results in an equal and opposite reaction force F′ acting upon the electrode portions parallel to the plasma column 28 at the closed end of the accelerator. The reaction force F′ and accompanying designating arrows are also shown in FIG. 1.

It is to be noted that since the plasma column 28 remains electrically neutral during the entire acceleration process, electrons do not have to be added to the accelerator exhaust. It is thus possible to produce thrust directly from electrical energy using electromagnetic forces and a neutral plasma. Furthermore, the amount of kinetic energy that can be added to the plasma is practically unlimited and specific impules of between about 2,000 and 10,000 seconds or more have been produced by this type of accelerator.

Important advantages can be attributed to a confined rail type pulsed plasma accelerator as compared with so-called "ion" type accelerators. Since the plasma accelerator is a pulsed device, it is possible to vary the thrust thereof by a factor of 1,000 or more by simply varying the pulsing rate. It is also possible to vary the specific impulse by varying either the amount of the admitted propellant or the quantum of energy discharged per pulse. Furthermore, the accelerator can be turned on or off instantly with no loss of propellant. In addition, a pulsed plasma accelerator can utilize a wide variety of easily stored and inexpensive liquified gases or solids as the propellant. And, of considerable operational importance the pulsed plasma accelerator is of simple and rugged construction and therefore capable of high reliability for long duration missions, while the ion type accelerator inherently requires rather close electrode spacings and delicate construction. Typical construction of a confined parallel rail pulsed plasma accelerator is illustrated in FIGS. 2-4. The elongate substantially parallel electrodes 32, 34 are enclosed in an insulative container 36 extending substantially the length of the electrodes and the electrodes are connected to an energy storage capacitor 38 by a short conical coaxial lead 40. Such a coaxial lead for example serves both as a low inductance electrical connection between the capacitor 38 and the electrodes 32, 34 and also can serve to distribute heat from the electrodes 32, 34 to the outside case of the capacitor 38.

The container 36, as shown, is closed at one end and open at the other, and can be fabricated from any suitable insulative

material. In the form shown, insulative container 36 in which the electrodes 32, 34 are housed is molded exteriorly around the electrodes and constituted of a suitable plastic or ceramic composition. As will be apparent, however, the container 36 in order to function in a desired manner can take various other forms, such as simply a pair of glass or ceramic plates placed against the electrodes.

Propellant is admitted through a small hole 42 in the rear of the enclosing container 36. The container in effect provides a plasma channeling chamber having a relatively narrow, confined volume extending substantially the entire length of said electrodes 32, 34. FIGS. 3 and 4 typically illustrate the narrowness of said channel.

Mounted above said insulating cover 36 and in direct communication with hole 42 is a modulator means 44 (also see FIG. 5).

FIG. 4 illustrates a lateral cross-section of the accelerator and typically illustrates the close spacing of the insulative container 36 about the two electrodes 32, 34. As shown in FIG. 4, the plasma chamber has a cross-section lateral to the direction of plasma movement which is bounded by electroconductive surfaces and insulative surfaces in alternating pattern, with the total surface area of said insulative surfaces being substantially greater than the total surface area of said electroconductive surfaces.

A confined parallel rail pulsed plasma accelerator may, for example, operate in either of two modes. The first mode consists of pulses on command in which single discrete pulses of propellant are admitted to the accelerator which will initiate a single discharge. The second mode consists of a continuous sustained series of repetitive pulses occurring as propellant is admitted in a continuous stream, with the energy storage capacitor allowed to recharge continuously. This continuous repetitive pulsation is best described as a cyclic sweeping clear of propellant from the plasma confining chamber by the discharge and refilling of said chamber by continuous propellant admission. The energy storage capacitor is recharged by the high voltage power supply that is continuously connected to it, and such recharging continues until sufficient propellant has refilled said chamber to cause another discharge. Such automatically continuous, repetitive pulse mode of operation can suitably occur at a rate of the order of 1,000 pulses per second.

Propellant admission to the pulsed plasma accelerator can be accomplished by any of the following techniques: (1) admission of a gas or vapor on command by means of a rapidly opening and closing valve, resulting in single pulse operation; (2) admission of a continuous stream or flow of gas or vapor, resulting in sustained repetitive pulsing operation; (3) admission of a continuous stream of gas or vapor which is cyclically modulated by a flow modulator such as an oscillating flapper valve; (4) insertion of a wire or other solid propellant by repetitive mechanical means; and (5) a combustible combination of liquids or gases, wherein the combustion reaction increases the propellant temperature and enhances ionization thereof, i.e. promotes plasma formation. In certain adaptations of pulsed plasma accelerators, propellant ionization can also be enhanced by placing in the accelerating chamber a radioactive material. Typical ionizable and vaporizable propellants are: water vapor, ammonia, carbon dioxide, nitrogen, oxygen, hydrogen, air, argon, helium, copper, Nichrome (the word "Nichrome" is a Trade Mark) and steel.

FIG. 5 is illustrative of a typical cyclic flow modulator for gaseous propellant. A vibrating spring or flapper member 46 is mounted within a narrow non-magnetic valve body 48 and is vibrated by a suitable solenoid 50, which is in turn actuated in a manner determined by the desired mode of operation. The action of magnetic forces created by the solenoid 50 on the oscillating flapper 46 causes it to vibrate up and down which alternately opens and closes the discharge orifice 52. Propellant enters the modulator 44 through the tube 54 and passes out of the modulator 44 in cyclic pulses. The flow modulator 44 preferably serves to create pulsations or "chops" in a continuous propellant flow rather than deliver discrete pulses of propellant.

Cyclically pulsing the propellant improves the control of the pulsing rate and control of the voltage to which the energy storage capacitor charges, with the result that propellant loss between capacitor discharges is significantly reduced.

A flow modulator or flow interrupter having a piezoelectric ceramic element to cyclically constrict the propellant flow path can also be employed. With use of a piezoelectric modulator element, a tap into the capacitor charging voltage can be used to actuate the piezoelectric element, so that capacitor charging and propellant "bursts" are synchronized. A magnetorestrictive propellant flow modulating element can likewise be employed, suitably with magnetorestrictive element actuation occurring responsively to the magnetic field produced by the previous current discharge.

FIGS. 6, 7, 7A and 7B illustrate various forms of confined rail accelerators typifying the present invention, incorporating a magnetic flux concentrating ferromagnetic sheath about the confined parallel rails. In these embodiments, the elongate electrodes 32, 34 and the insulative container 36, are

surrounded by a ferromagnetic sheath. Specifically, in the form shown at FIGS. 6 and 7, sheath 60 is an epoxy resin impregnated with particulate magnetic material such as dispersed iron particles, the iron content being about 90% by weight, for example. The ferromagnetic sheath 60 serves as a flux concentrator and greatly increases and makes more uniform the self-induced magnetic field produced by the current in electrodes 32, 34 and in the plasma column, by virtue of the fact that the concentrator pole pieces (sheath faces 62, 64) are closely spaced to each other across the current flow path. Thus the plasma zone between electrodes 32, 34 surrounded by the insulative cover in which the plasma column is confined and accelerated is subject to a much higher magnetic flux or field than would otherwise occur. FIG. 7 is a lateral cross-section of the embodiment shown at FIG. 6, further illustrating the arrangement of electrodes 32, 34, insulative container 36, and iron powder-resin ferromagnetic magnetic flux concentrating sheath 60. FIG. 7 also further illustrates the relative close spacing of the ferromagnetic sheath pole pieces 62, 64.

FIG. 7A illustrates a modified form of flux concentrating ferromagnetic sheath used in conjunction with the electrode rails 32, 34 and the insulative container 36. Specifically, in this form of the invention, the ferromagnetic sheath 60′ is in the form of compressively packed or sintered iron particles within an epoxy resin protective coating 61.

FIG. 7B illustrates another modified form of flux concentrating sheath 60″, used in conjunction with the spaced electrodes 32, 34 and the insulative cover 36. In this form of augmentation sheath, a series of thin sheets of transformer iron 56 (of 16 mils or less thickness, for example) extend substantially perpedicularly of the electrodes 32, 34 and are interleaved with an even thinner insulating sheet 58. As will be apparent, the transformer iron sheets 56 each have the major dimension thereof extending across the direction of flow of the plasma and generally in planes of current flow of the plasma arc.

It is characteristic of all of the forms of flux concentrating sheaths shown in FIGS. 7, 7A and 7B that an increased magnetic flux is self-generated from the current flow in the electordes 32, 34 and in the plasma arc (current 28′) in a direction to accelerate the plasma flow. It is a further important characteristic of the use of a ferromagnetic sheath to self-induce increased flux density across the narrow dimension of the plasma zone that a high magnetic field is produced only at the point where the plasma is located at any given instant. There is therefor no high residual circuit conductance, i.e. the magnetic field produced is essentially entirely a useful field insofar as plasma acceleration is concerned. This improved mode of operation is to be distinguished from the proposition of applying an externally generated magnetic field, such as by externally excited coils or the like, or by external permanent magnets, since a continuously excited non-self-induced field either wastes power (if electrically energized) or is unduly heavy (if a permanent magnet arrangement). Without a self-induced field, the field does not reverse when the plasma current reverses, and diminished or negative acceleration forces result.

An experimental confined rail accelerator can employ, for example, an electrode spacing of 2 1/2 inches with 1/4 inch diameter electrodes 1 foot in length, an insulative container providing a plasma channeling chamber 1/4 inch thick, a capacitor of 15 microfarads, a 2.5 kv voltage source, and a helium propellant. An accelerator so constructed, and operated in a "pulsed on command" mode, exhibited an efficiency (useful kinetic energy in the exhaust divided by the stored energy in the capacitor) of 48% at 5100 seconds specific impulse. With an appropriate ferromagnetic sheath 60 or 60′ or 60″ added, as shown in FIGS. 7, 7A and 7B, the efficiency of the accelerator is increased to about 75% at the same specific impulse, and the magnetic field thereof is considerably more uniform, i.e. considerably more evenly distributed across the plasma channeling chamber. The flux density in the accelerating channel increases by a factor of about thirteen for any given circuit current as a result of the use of the ferromagnetic sheath. The increase in efficiency resulting from use of a flux concentrating ferromagnetic sheath becomes even more pronounced as the spacing between the electrode 32, 34 is increased and as the interpole gap dimension is reduced. Optimizing circuit parameters and utilization of a ferromagnetic sheath in conjunction with a confined rail pulsed plasma accelerator acording to the present invention, appears to have an efficiency capability as high as about 95% of theoretical at about 5000 seconds specific impulse. Correspondingly, use of a ferromagnetic sheath makes possible efficiencies of about 50% of theoretical at 1000 seconds specific impulse, whereas the efficiency capability otherwise is only about 15% of theoretical. Of notable importance, also is the fact that use of a ferromagnetic sheath is practical only in conjunction with a confined rail pulsed plasma accelerator, since parallel rails provide the only pulsed accelerator configuration compatible with use of opposed magnetic pole faces with a narrow gap therebetween.

Also of important practical significance is the fact that the length and therefore the weight of the ferromagnetic sheath and associated accelerating channel can be kept small because the sheath provides a high ratio of final to initial inductance. Engine miniaturization is quite practical with accelerator configurations according to the invention. A typical confined rail micro-engine utilizing a ferromagnetic sheath can involve 1/8 inch diameter electrodes 4 inches long spaced 1 inch apart, a ferromagnetic sheath thickness of 1/8 inch and a total channel weight of only 1/2 pound, for example.

As earlier indicated, the confined parallel rail pulsed plasma accelerator can be operated in a continuous repetitive pulsing mode by the continuous admission of a stream of gaseous propellant and, furthermore the accelerator operates on a wide variety of gaseous propellants, including air. These properties of the confined parallel rail pulsed plasma accelerator give rise to several advantageous operational possibilities: (1) operation within the earth's atmosphere using the atmosphere directly as a propellant source, including the operation of the accelerator as a continuously self-fed ramjet; (2) collection and condensation of the earth's atmosphere while within the atmosphere, with use of the collected atmosphere as a propellant for a part of or the remainder of the space mission; (3) operation as in (1) and (2) further utilizing the atmosphere and/or surface materials of a foreign planet as the propellant source.

WHAT WE CLAIM IS:—

1. A pulsed plasma accelerator for generating propulsion thrust, comprising a pair of spaced, elongate substantially parallel electrodes of substantially equal cross-sectional area, a high voltage power supply connected across said electrodes, an electrical energy storage capacitor connected across said electrodes, an insulative container surrounding and being substantially coextensive with said electrodes at the sides and at one end thereof, leaving the other end open, and providing a plasma channelling chamber between said electrodes, a flux concentrator disposed laterally of the insulative container to provide an increased flux density therebetween, and means for delivering and injecting a vaporizable and ionizable propellant into the closed end of said container.

2. A pulsed plasma accelerator as claimed in claim 1, wherein said means for delivering and injecting a vaporizable and ionizable propellant comprises means for varying the amount of propellant injected.

3. A pulsed plasma accelerator as claimed in claim 1, wherein said means for delivering and injecting a vaporizable and ionizable propellant comprises means for varying the rate of propellant injection.

4. A pulsed plasma accelerator as claimed in claim 3, wherein such propellant delivery and injection means comprises means injecting the propellant into the chamber continuously.

5. A pulsed plasma accelerator as claimed in claim 4, wherein said propellant is a gas and said propellant delivery and injection means comprises a vibratory type flow modulator, the continuous injection of the gas into the container being characterized by a cyclic pulsation.

6. A pulsed plasma accelerator as claimed in claim 1, wherein said vaporizable and ionizable propellant is a gas.

7. A pulsed plasma accelerator as claimed in claim 6, wherein said gas is ammonia or water vapor.

8. A pulsed plasma accelerator as claimed in claim 1 wherein a ferromagnetic flux concentrator laterally surrounds said insulative container in a manner placing magnetizable pole pieces substantially against the side faces of said container so that plasma current self-induces an increased flux density within the plasma zone between said electrodes, with the flux lines thereof paralleling the thickness dimension of said container.

9. A pulsed plasma accelerator as claimed in claim 8, wherein said ferromagnetic flux concentrator is composed essentially of a laminate of ferrous sheet material with interleaved insulative sheet material, the major dimension of the ferrous sheet material extending generally laterally of the direction of plasma movement in said plasma channeling chamber.

10. A pulsed plasma accelerator as claimed in claim 8, wherein said ferromagnetic flux concentrator is fabricated essentially of a resin impregnated with particulate magnetic material.

11. A pulsed plasma accelerator as claimed in claim 8, wherein said ferromagnetic flux concentrator comprises compacted iron particles with an external protective coating.

12. A pulsed plasma accelerator wherein a vaporizable ionizable propellant is injected into a plasma accelerating chamber open only at one end, said chamber in cross-section thereof lateral to the direction of plasma movement being generally rectangular in configuration and bounded by electroconductive surfaces and insulative surfaces in alternating pattern, the total surface area of said insulative surfaces being substantially greater than the total surface area of said electroconductive surfaces, there being a flux concentrator disposed laterally of said insulative surfaces to provide an increased magnetic flux density

therebetween.

13. A pulsed plasma accelerator substantially as hereinbefore described with reference to and as illustrated in the accompanying drawings.

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1,181,431 COMPLETE SPECIFICATION
2 SHEETS *This drawing is a reproduction of the Original on a reduced scale.*
SHEET 1

Fig. 1.

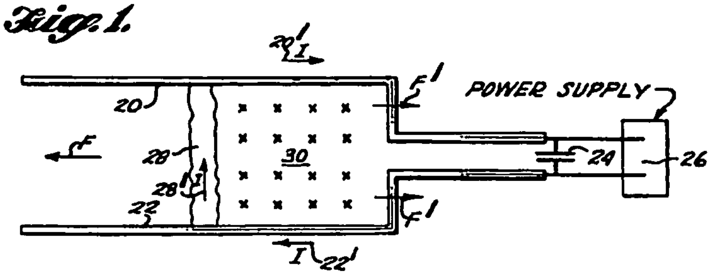


Fig. 2.

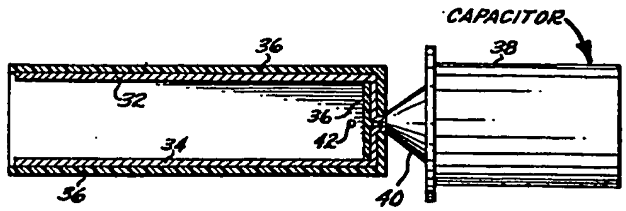


Fig. 3.

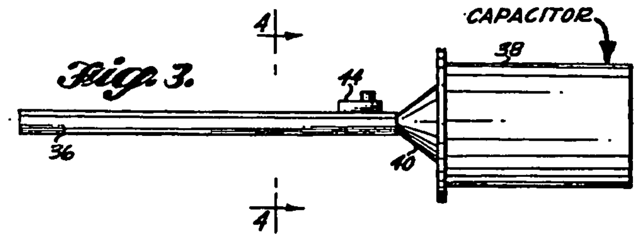
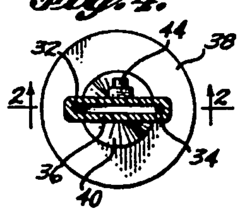


Fig. 4.



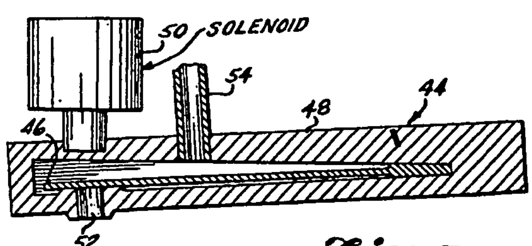


Fig. 5.

Fig. 6.

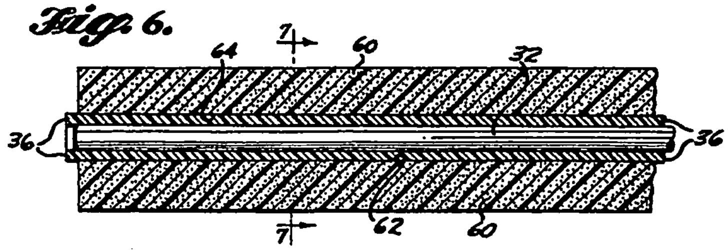


Fig. 7.

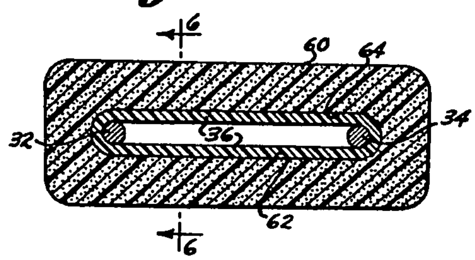


Fig. 7A.

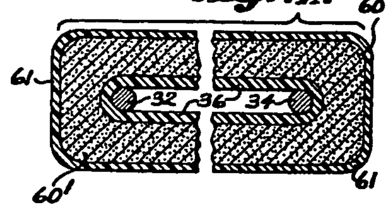


Fig. 7B.